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# SIGNIFICANCE OF FINITE ELEMENT METHOD BASED MODELING IN ANALYSING TEMPERATURE GENERATION AND DISTRIBUTION DURING HARD TURNING

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***ABSTRACT***

***Manufacturing Industries play a very key role in the development of any country. Machining forms a very important segment of manufacturing industries and turning has a crucial role to play in machining. Need to machine high strength material and the requirements of specialised industries have resulted in the evolution of hard turning. Improving the efficiency of the turning process and understanding its effects through modeling have always remained an active area of research. The primary objective of this paper is to provide a detailed insight into heat generation process during turning. A review about how different researches have exploited Finite Element Analysis to model the heat generation and distribution is also presented. The paper also elaborates on the commercial tool that has been used by the research community for performing Finite Element Analysis.***

***KEYWORDS:** Machining, Hard Turning, Heat Generation, Finite Element Analysis*

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## 1. INTRODUCTION

Machining plays a key role in the manufacturing set-up and helps to produce products that accurately match the design specification. Machining finds a critical role in maintaining the form and shape of the products being manufactured. The material removal process is very essential to deliver a product that satisfies the design specifications. The term “machining” includes a wide gamut of manufacturing processes designed to remove material from a work piece [1]. The primary machining processes encompass different operations like turning, milling, sawing, and abrasive machining. In the case of turning, a single point cutting tool removes the material from the surface of the work piece which rotates at a constant speed. Turning has multiple applications across different industrial segments. Traditionally, the turning process has been employed to reduce the diameter of a cylindrical work piece (or) to change a work piece of non-circular cross section [1]. This reduction in diameter can be brought about by rotating a work piece on its axis on a machine spindle and having the tool piece travel perpendicular to the axis of rotation.

The turning process is carried out on a lathe that provides the power to impart a defined rotational speed and the necessary power to feed the tool at specified rate. In order to have an efficient turning process, parameters like cutting speed, feed rate, depth of cut, tool geometry and cutting conditions need to be optimized [2].

Hard turning attributes its origin and development in the automobile industry. Hard turning focused its initial applications in the machining and manufacturing of transmission lines for the automobile sector. It offers multiple advantages like reduced equipment cost, reduced set-up times and fewer process steps and impart high flexibility and ability to cut complex geometries. This technology has evinced keen interest in the research community and consequently, many research studies have been carried out to understand and analyse the attributes of turning process.

Temperature generation and distribution within the cutting zone plays very crucial role in defining the influence on inherent properties of the tool and the work piece. The heat generated has a severe impact on the wear and tear of the tool. The heat generation regions can be classified in to three zones, the primary zone being the shear zone, the secondary zone or the tool-chip interface zone and tertiary zone being the tool-work piece interface zone [3]. In the energy expended in doing the work of turning, much of it is converted to heat. This heat can be attributed to the plastic deformation of the work piece and also to the friction generated at the tool-chip interface and the tool-work piece interface.

The machining process results in a increase in the temperature of the cutting zone which in turn affects the structural integrity of the material. This enhances the tool damage and can also result in loosing dimensional accuracy and surface integrity. The increased temperature can also cause damage to the work piece affecting its inherent qualities. Different cutting parameters have their influence on the cutting zone temperature. Similarly the property of the work piece material and that of the tool also influence process of heat generation and distribution [3]. It is imperative to measurement and predicts temperature of tool, chip and work piece during the metal cutting process

Unsatisfactory tool life and limitation on cutting speed are some of the ill effects of high temperatures experienced during the machining process. A multitude of numerical and experimental procedures are available for studying the generation and distribution of heat during the cutting process. These techniques are used for predicting the heat flow and its distribution within the tool and the work piece. The increased use of ceramic material coupled with the use of high speed machinery with higher cutting speeds has greatly enhanced the significance of studying the role of temperature. Various heat transfer scenarios like heat conduction across the contact zone, radiation, heat conduction, free convection along the external surfaces , forced convection along the rotated elements should be suitably incorporated in to any thermal model that is designed for machining process [4].

It is very important to analyze the effect of temperature on the performance of the machining process; experimental studies in metal cutting are expensive and time consuming. In addition, the results are valid only for the specific experimental conditions used. The results also depend on the accuracy of the calibration of the experimental equipment. So it is imperative to develop numerical models to understand and analyze the temperature effects. Experimental approaches have difficulty on many counts and are intensively time consuming .Similarly it’s almost impossible to design and analyze multiple scenarios in a experimental setup. To circumvent the disadvantages of experimental setups other approaches like modeling and numerical methods are employed. They can be applied in calculating the temperature distribution and thermal deformation in the tool, chip, and work piece, some of the methods are; (a) Finite Difference Method (FDM) ,(b) Finite Element Method (FEM) ,(c) Boundary Element Method (BEM). Finite Element Method (FEM) is one of the most frequently used numerical methods to study the machining process. The process of machining being a multidisciplinary aspect with influence being exerted metallurgy, elasticity, plasticity, heat transfer, lubrication and fracture mechanics. Finite Element Analysis (FEA) helps in arriving at a complex computational model that can help in predicting the stress, strain, plastic deformation and other factors experienced by both the tool and the work

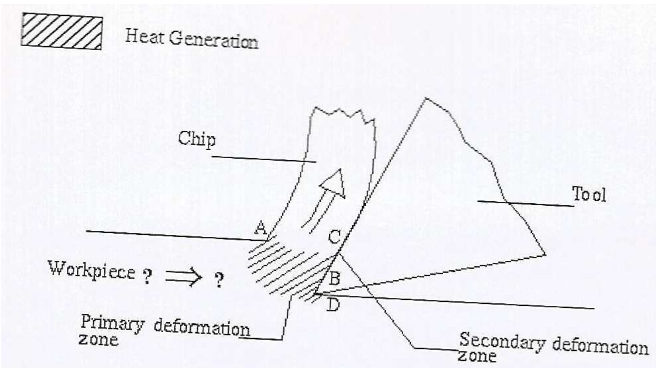
piece. All these factors are influenced by machining and a have a direct bearing on the quality of the machining process and tool life.

This paper is organized in to two sections, with one section dealing with generation and distribution of heat and other dealing with Finite Element Analysis (FEA). This is expected to give an insight in to the turning process and how different researchers have used Finite Element Analysis (FEA) for analyzing temperature distribution during turning process. A survey of literature is conducted and conclusion arrived at. A brief review about commercially available Finite Element Analysis (FEA) tools is also presented. This paper contributes towards understanding of temperature generation and distribution and how it can be modeled using Finite Element Analysis (FEA) to help researchers in evolving new methods of analysis.

**2. Temperature in Turning**

Temperature gradient and its distribution severely affect the tool and the work piece material property and also exert considerable influence on the tool wear. In order to analyse these effects and understand their significance, it is important to model the generation and distribution of temperature. The heat generation has 3 regions that can be clearly demarked. It has a primary shear zone, the tool-chip interface (or) the secondary deformation zone and the tool – work piece interface zone. Heat is dissipated from the primary, secondary and tertiary zones by the chip, the tool and the work piece.

The Figure 1 Illustrates the dissipation of heat. The temperature rise in the cutting tool can be primarily attributed to the secondary heat source but the contribution of the primary heat source can also not be discounted. The primary heat source tends to increase the temperature rise of the cutting tool and indirectly affects the temperature distribution on the tool rake face [5, 6].




**(Image source: http://www.mfg.mtu.edu/)**

**Figure 1: Dissipation of Heat in Machining**

During the machine cutting process, convection heat flow causes the transfer of heat through chip and then through the interface dissipating in to the cutting zone. Thus the heat generated in the shear zone has a direct influence on the both the tool and tool chip interface. Temperature increase in the tool rake face can be attributed to the heat generated in both the primary and the secondary zones [6]. Increase in temperature is one of the primary reasons for dimensional errors. There is an increase in the elongation of the cutting tool which alters its position and shifts the tool edge towards the machined surface. This can cause a dimensional error around 0.01-0.02 mm. Owing to the transient nature of heat generation and dissipation, a time is necessary to achieve steady state condition. The discarded chip carries away most of

the heat to the tune of 60% to 80 % of the total heat generated [6]. The workpeice and the cutting tool also dissipate heat to the tune of 10%-20% and 10 % respectively.

The rate of energy consumption in metal cutting is given by:

$$WC = F_V V \tag{1}$$

Where, $F_v$ is the cutting force and V (m/sec) is the cutting speed.

Assuming all the work done is converted in to heat [5, 6], the heat generated in the primary deformation zone can be defines as

$$Qr = F_v V \tag{2}$$

The amount of heat generated in the secondary deformation zone can be represented using the equation (3) which considers the frictional energy generated during the machining process

$$QS = F_{Fr} V/\mu \tag{3}$$

Where, $F_{Fr}$ is the total shear force acting on the rake face (N), V is the cutting speed (m/s) and μ is the chip thickness ratio.

The force $F_{Fr}$ is computed using the following equation:

$$F_{Fr} = F_V \sin\alpha + Fs \cos\alpha \tag{4}$$

Where, Fv defines the cutting force, Fs gives the feed force and α is the rake angle.

One of the most difficult and complicated aspect of metal cutting is the process of temperature estimation. The complex nature of interaction between the point of contact of tool and the work piece, it is very difficult to model these interactions and analyze their influence on temperature generation and distribution. The complexity of the contact phenomenon makes it difficult to have any accurate prediction of the temperature generation and distribution process. The process of exact measurement of tool chip temperature is extremely difficult and lack of experimental data , makes it very hard to compare and validate the performance of any model. The literature presents numerous attempts that have been made to model and measure temperature changes during the machining process [7]. An analytical prediction method was developed by Lowen and Shaw [8] and they concluded that the cutting temperature is a function of speed and feed rate. They defined the average cutting temperature as

$$At = V^{0.5} f^{0.3} \tag{5}$$

Where $At$ is the average cutting temperature, $V$ is the cutting speed and $f$ is the feed rate.

It is also important to observe that the cutting temperature distribution is not uniform throughout the tool and the work piece. A temperature gradient is usually observed along the tool chip interface

The heat generated during the metal cutting process is due to the plastic deformation energy that transforms itself into the form of heat. The heat generation rate, Q (W), is given by Sata and Takeuchi [9, 10] as:

$$Q = 1.68\, a\, f^{0.15} V^{0.85} \tag{6}$$

A variety of tools like radiation pyrometers, thermocouple, calorimetric techniques are employed for measuring

the chip tool interface temperature. The method of measuring the temperature using thermocouple is profound and widely used. Other methods usually suffer from disadvantages like complications during measurement, slow speed of response and inaccuracy.

**3. Finite Element Analysis and Turning**

Complex shapes of geometric objects and their physical properties can be constructed with the help of mathematical modeling through computers. They are referred to as Finite Element Method (FEM) and the analysis through these methods as Finite Element Analysis (FEA). FEA is tool is versatile in that it can handle irregular shapes and can be employed for analyzing materials with heterogeneous properties.

R. Courant during the year 1943 first proposed the concept of Finite Element Analysis (FEA). He employed Ritz method of numerical analysis. R. Courant also utilized minimization of variation calculus to propose solutions for vibration systems. The broader definition of numerical analysis was provided by Turner MJ et al... in 1956. These definitions were provide by them through a paper published about "stiffness and deflection of complex structures" [11. Advances in computation and processing power have made Finite Element Analysis one of the most efficient and accurate method for modeling and analyzing different field variables. The applications for FEA include, stress analysis, analysis of heat flux, magnetic flux etc…The below section describes how the approach of Finite Element Analysis is used in analyzing the temperature distribution in machining process, through review of literature.

Most of the approaches employed for numerical modeling to describe and analyze metal cutting processes falls under Lagrangian and Euclerian techniques. There is also one combinatorial technique by the name arbitrary Lagrangian-Euclerian formulation [12, 13]. In these techniques the mesh is attached to the work piece and the Lagrangian formulation is used. Johnson and Cooks employed constitutive equation to perform FEA with three different set of material constants. They employed FE model to analyze the behavior of Ti6Al4V alloy used in the machining process for both conventional as well as high speed operations [14]. The need to have higher productivity and demand for good quality products has dawned upon many researchers to pursue and analyze the machining parameters[15].

Different types of experimental and analytical procedures have been carried out to determine the amount of heat generated and dissipated during the machining process. Analytical and numerical procedures have also been employed to calculate the average and peak temperature at shear zone and where the primary, secondary and tertiary deformation takes place. These methods were applied for both stationary as well moving heat sources. Similarly the conduction effects of heat were also analyzed and the unknown boundary of heat flux was obtained using the interior heat distribution [16]. A numerical solution which considers a three dimensional heat diffusion equation for both the tool and tool holder assembly was proposed by S.R. Carvalho, S.M.M. Lima e Silva, A.R. Machadoa, and G. Guimaraes [17]. They employed Finite Element Method (FEM) to model the heat flow. A successful implementation of FEM was employed by. Asmaa A. kawi [18] to estimate cutting temperatures.

Mofid Mahdi, Liangchi Zhang [19] employed FEM to develop a 2D cutting force model by considering chip breaking. They carefully analyzed the variation of cutting force against anisotropic materials and cutting parameters. H.S. Qi, B. Mills [20], employed the concept of the cutting interface and developed a new flow zone model during turning process. The proposed model was dynamic model and explained in detail the dynamic contact behavior between chip and the tool.Tugrul Ozel, Taylan Altan [21], adopted FEM and delivered a new approach to determine concurrently (a) the flow

stress at high deformation rates and temperatures that are encountered in the cutting zone, and (b) the friction at the chip–tool interface. Xiaoping Yang, C. Richard Liu [22] designed a novel stress –based model to describe the frictional behavior during the machining process. They demonstrated the feasibility of the model using FEA. They also performed a sensitive study and compared the different results delivered by the model. Finite element based simulation have also been successfully applied for modeling metal cutting simulations based on Langrangian techniques [16]. Pradip Mujumdar [23] proposed a finite element based computational model to analyze the temperature distribution in a metal cutting process. The model proposed in [23] was based on multi dimensional heat flow equations and they also accounted for heat loss with the help of convection film coefficients at the surface. It also incorporated models for heat generations within primary and secondary zones. They validated the approach by presenting the results for high speed machining of carbon steel for a range of cutting conditions.

W. Grzesik [24] employed FEM to investigate the suitability to obtain solutions for cutting forces, specific cutting energy and adequate temperature for a range of coated material .The various thermal simulation results were compared with the measured cutting temperature. Different researchers have developed different methods for accurately predicting the effects of machining process.

**4. Software Tools for Finite Element Analysis**

A wide gamut of commercial software is available to do Finite Element Analysis (FEA). This section reviews some of that software which is widely used

**MultiMech** [25] is one of the commercially available software packages that is stand alone and can be employed for solid structural analysis. This desktop based FEA solver comprises of a preprocessor, a proprietary solver and a post processor. It also has the capability to import models from other FEA software packages like Abaqus

Multiscale solutions can accommodate micro structural details and can be used to estimate microstructural damages within a given model. These micro structural damages include analysis of, matrix cracking, fiber breaks, fiber – matrix deboning and delamination. These micro structural analyses are very important because many physical tests have validated the significance of these materials in impacting the overall material properties.

**ADINA** [26] is the acronym for Automatic Dynamic Incremental Nonlinear Analysis. The ADINA program consists of four core modules:

- *ADINA Structures* for linear and nonlinear analysis of solids and structures
- *ADINA Thermal* for analysis of heat transfer in solids and field problems
- *ADINA CFD* for analysis of compressible and incompressible flows, including heat transfer
- *ADINA EM* for analysis of electromagnetic phenomena

These modules can be used fully coupled together to solve multiphysics problems, where the response of the system is affected by the interaction of several distinct physical fields (e.g. fluid-structure interaction, thermo-mechanical analysis, piezoelectric coupling, Joule heating, fluid flow-mass transfer coupling, electromagnetic forces on fluids and structures, etc.)Also, included in the ADINA suite of programs is a graphical user interface (known as the ADINA User Interface, or AUI) with a solid modeler, ADINA-M, for the pre- and post-processing tasks. The AUI can be used to import solid models, and finite element models in Nastran format, providing an interface to many CAD and CAE packages.

Furthermore, as part of the ADINA suite, Femap can be used for the pre- and post-processing of ADINA data in structural, CFD, and FSI analyses.

**Abaqus FEA** [27] released in 1978 is a software suite that can be used for Finite Element Analysis (FEA) and Computer Aided Engineering (CAD). It can be used for both modeling and analysis of mechanical components and assemblies. It is also used for visualizing the finite element analysis result. It has an independent Abaqus / Viewer which can be used for analyzing the post processing data. It finds application in automotive, aerospace and industrial production sector. Abaqus also finds wide application in academic and research institutions and provides a good collection of multiphysics capabilities, such as coupled acoustic-structural, piezoelectric, and structural-pore capabilities. It is one of the most attractive tool for production-level simulations and is typically suitable where multiple fields need to be coupled.

**ANSYS Mechanical** [28] is a comprehensive FEA analysis (finite element) package for structural analysis. It includes capability to study linear and non linear dynamics. It is capable of tackling a wide range of design problems with the help of different set of elements and solvers which can help in understanding material behavior. coupled-physics capabilities involving acoustic, piezoelectric, thermal–structural and thermo-electric analysis are provided in addition to thermal analysis in ANSYS Mechanical. NSYS structural analysis software offers various advanced modeling methods for different kinds of applications and comprises a solid foundation of element and material technology. A variety of physics phenomena, such as thermal–stress, electromechanical, structural–acoustics, mass diffusion and simple thermal–fluid analysis can be analyzed with the help of ANSYS. ANSYS structural analysis suite comprises of a large library of out-of-the box equation solvers. The library has among others, the distributed versions of PCG, JCG, the sparse direct solver, preconditioned conjugate gradient (PCG) iterative solver, Jacobi conjugate gradient (JCG) solution and more. By combining our parallel algorithms with the power of GPUs, one can reduce the computation time to a great extent for solving the large scale problems.

The post processing module in ANSYS helps in understanding and displaying comprehensive results of models as contours and vector plots. They can also provide summaries of the results like the maximum, minimum occurrences and their location. The detailed results of the given geometry can be analyzed with the help of powerful slicing tools. These results can also be exported as texts or spread sheets for future calculations. Similarly animations can also be included for nonlinear or transient states as well as for static cases. Boundary conditions and results can be employed for creating customized charts.

## CONCLUSIONS

Understanding the dynamics of the turning plays a critical role in increasing the efficiency of the machining process, reducing wastage and limiting tool damage. In this paper, a comprehensive review about the generation of heat during machining and how different researchers have modeled it have been presented. This paper also demonstrates the importance of Finite Element Analysis in understanding temperature generation and distribution during the turning process. It can be clearly inferred through the study of literature that the Finite Element Analysis is one of the most acceptable and widely used methodology for modeling heat generation and distribution. Finite Element Analysis also provide a great scope for analysing heat generation and distribution under different dynamic conditions. This greatly enhances the flexibility of Finite Element Analysis and provide a great advantage over experimental methods. The Finite Element Analysis also shows a very high degree of acceptance among the industrial users and any solution of research using Finite Element Analysis will be accepted and appreciated.

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